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Heavy Quark Production at a Linear e^+e^- and Photon Collider and its Sensitivity to the Gluon Content of the Photon

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Abstract

A high energy linear e^+e^- collider (LC) can also be used as a Photon Collider (PC), using Compton scattering of laser photons on the e^+/e^- beams. The leading order cross-section for the production of heavy quarks, $e^+e^- \to e^+e^- Q(\bar{Q})X$, at high transverse momenta is calculated for both LC and PC modes. The sensitivity of this process to the parton distribution parametrizations of real photons, especially the gluon content, is tested for both modes.

For the study of a future electron-positron Linear Collider (LC) it is important to examine the physics potential for its main and possible derived options. The so called Photon (or Compton) Collider (PC) is an option in which high energy real photons can be obtained by backscattering photons from a laser beam on the electron or positron beam [1, 2]. This way an excellent tool for the study of $\gamma\gamma$ collisions at high energies can be constructed.

In high energy e^+e^- collisions the hadronic final state is predominantly produced in $\gamma^\star\gamma^\star$ interactions where the virtual photons are almost on mass shell. These processes can be described by an effective (real) photon energy spectrum, i.e. using the Weizsäcker-Williams (WW) approximation. A Photon Collider based on Compton scattering, however, provides beams of real photons, which can be produced in a definite polarization state and with high monochromaticity. Moreover, the resulting photon spectrum (denoted as LASER) is much harder then the WW one. The comparison of the photon spectra used in this analysis (see Appendix) is presented in Fig. 1.

The main goal of this work is to compare the LC and PC opportunities for probing the gluon distribution in the photon, without making use of polarization. Heavy quark production in the unpolarized electron-positron scattering $e^+e^- \to e^+e^-Q(\bar{Q})X$ is a promising process for such a study, see e.g. [3, 4] and also [5], where the related topic is considered. The measurement of this process is also an important test of QCD by itself. Heavy quarks can be produced in $\gamma\gamma$ collisions through three mechanisms. Direct (DD) production occurs when both photons couple directly to the $Q\bar{Q}$ pair. In single resolved photoproduction processes (DR) one of photons interacts via its partonic structure with the second photon. When both photons split into a flux of quarks and gluons, the process is labelled a double resolved photon (RR) process.

Calculations for processes involving heavy quarks are performed in two schemes. They differ by the number of quark flavours which are considered to be part of the structure of the photon, and thus can take part in the process as partons. In the case of the massive scenario, the so called Fixed Number Flavour Scheme (FFNS), the photon "consists" only of light quarks and gluons, which may interact, and massive heavy quarks can be only created e.g. via gluon-gluon fusion. The massless Variable Number Flavour Scheme (VFNS) considers apart from the gluons and u, d and s quarks also heavy quarks as active flavours, which are all treated massless. This scheme is expected to be valid only for $p_T >> m_{c(b)}$. All the partonic reactions contributing in LO to heavy quark production in these schemes are shown in table 1.

We calculate in LO QCD the production rates for c and b quarks produced with large p_T for the e^+e^- colliders LEP and LC at energies of 180 GeV and of 300, 500 and 800 GeV, respectively, and for the $\gamma\gamma$ PC based on the corresponding (e^+e^-) LC collider. We test the sensitivity of considered processes to the gluonic content of the photon by using two different parton density parametrizations for the real photon: GRV[6] and SaS1d [7]. Both these parametrizations were extracted from QCD fits to photon structure function data measured in $e\gamma$ collisions from e^+e^- interactions, but have different assumptions for the gluon content, which is only weakly constrained by these measurements. The GRV and SAS1d distributions both start the evolution from a small starting scale, $Q_0^2 = 0.25$ GeV^2 and 0.36 GeV^2 respectively, a procedure which has turned out to be quite successful for the parton densities in the proton. Consequently both parton densities predict a rise of the gluon density at small x. The different treatment of the vector meson valence quark distributions leads to a larger gluon component at small-x of the photon for GRV compared to SAS1d.

In the massive (FFNS) calculations the number of active flavours (N_f) is taken to be 3. In the massless (VFNS) scheme it varies from 3 to 5 depending on the value of the hard (factorization, renormalization) scale μ. Heavy quarks are included in the computation provided that $\mu > m_c$ (m_b) with $m_c = 1.6$ GeV ($m_b = 4.5$ GeV) being the mass of c (b) quark. When charm production is calculated in the VFNS the bottom quarks are always excluded, hence $N_f = 3$ or $N_f = 4$. Also the QCD energy scale Λ_{QCD}, which appears in the one loop formula for the strong coupling constant α_s, is affected by change of the number of active flavours. Therefore we denote it as $\Lambda_{QCD}^{N_f}$. We take this scale to be:

$$\Lambda_{QCD}^3 = 232 \qquad \Lambda_{QCD}^4 = 200 \qquad \Lambda_{QCD}^5 = 153\,\mathrm{MeV} \tag{1}$$

as in [6]. If not stated otherwhise the hard scale in the calculation of the cross-section μ is taken to be the transverse mass of the produced heavy quark $m_T = \sqrt{m_Q^2 + p_T^2(Q)}$.

Both resolved photon contributions (DR and RR) to the process $e^+e^- \to e^+e^-Q(\bar{Q})X$ are dominated by reactions initiated by gluons, especially in the PC kinematic regime. This can be seen in Fig. 2, where the individual contributions to the differential LO cross-section are presented for the charm quark production. We study $\frac{d^2\sigma}{dp_T^2 dy}$, with $y = \frac{1}{2}\ln\frac{E-p_L}{E+p_L}$ being the rapidity of the produced heavy quark and p_T its transverse momentum. The results were obtained in the VFNS scheme for both types of initial photon spectra. A fixed energy $\sqrt{s}$=500 GeV and p_T =10 GeV for the charm quark was assumed. The calculation was performed using the GRV parton parametrization. The dominance of the gluon over the quark contribution is larger for the PC spectrum; it is also larger in the FFNS scheme (not shown) compared to the VFNS one.

Fig. 3 shows the differential cross-sections for charm quark production with p_T=10 GeV for the direct, single resolved, double resolved and total contributions. The results were obtained in the VFNS scheme using the GRV parton distribution. An interesting pattern is observed. In case of the e^+e^- LC with a WW photon spectrum either the process is dominated by direct photons coupling to heavy quarks, or resolved and direct contributions are found to be of the same importance. The DR and RR contributions increase with increasing energy. Nevertheless in the range of the anticipated LC energies, the gluon induced reactions do not play the dominant role for heavy quark production. The opposite is found for a PC: heavy quark production is always dominated by resolved photon interactions. The direct contribution becomes even less important with increasing centre of mass system energy. Hence, the charm production cross-section is much more sensitive to the parton distribution parameterization of the photon for a PC compared to a LC. Since for the PC option the resolved photon contributions are clearly dominated by the processes involving gluons (Fig. 2) this option offers an excellent tool for measuring the gluonic content of the photon.

For the VFNS scheme and the PC option we have checked (not shown) that processes initiated by heavy quarks in the photon constitute about 52-67% of the total cross sections presented in Fig. 3, and about 99% of the contribution which arises due to the processes initiated by quarks. Since the heavy quark content of the photon is closly related to the gluon density in the photon, the heavy quark production discussed in the paper exhibits also sensitivity to the gluonic density via the heavy quark content of the photon. Due to the fact that the LC option has a large contribution from the direct process, this effect should be most visible for the PC case, which is dominated by the resolved photon processes instead.

An important feature of the results is the observed rise of the resolved photon process contribution, and therefore also an increasing sensitivity to gluons (see below), with increasing energy. This results from the fact that higher energies explore regions of small Bjorken-x_γ values. The minimal x_γ value reached for $p_T = 10$ GeV varies from ~ 0.01 for $\sqrt{s} = 180$ GeV to ~ 0.0006 for $\sqrt{s} = 800$ GeV. At the same time the gluon distributions differences for the GRV and SaS1d parametrizations are large for small x_γ values. These results are not affected by the choice of the scheme for the heavy quark calculation (see Fig. 4): for both the FFNS and VFNS the cross-section is 20-30 times larger for the PC than for the LC.

The sensitivity of the considered process to the gluon distribution is studied further by comparing the predictions obtained using two different parton parametrizations for the photon. In Fig. 5 and 6 the ratio of the relative difference of cross-sections $\frac{d^2\sigma}{dp_T^2 dy}$ is presented, obtained using the GRV and SaS1d parton distribution parametrizations in the VFNS and FFNS schemes. As expected the PC photon spectrum leads to a larger sensitivity than the WW spectrum for a given energy of the e^+e^- collider: the difference between the two structure function parametrizations shown is 5-20% for a WW and 25-40% for a PC photon spectrum.

We presented here only the results for c quark production. The corresponding b-quark production (not shown) has all the features listed above though the difference between the sensitivity to the gluon distribution at a PC compared to a LC is smaller. All calculated cross-sections for beauty production are found to be even more sensitive to the gluonic content of the photon than the corresponding ones for charm production, but the cross-sections are smaller, see also below.

Our calculation predicts a high number of the heavy quarks, c and b, produced at the considered centre of mass energies of the e^+e^- collider of 300, 500 and 800 GeV for both the LC and PC options. The event numbers are given in Table 2 assuming an e^+e^- integrated luminosity of 100 fb^{-1}, which could be achieved at a high luminosity LC with one year of running, and for $p_T > 10$ GeV. In practice, charm with a $p_T > 10$ GeV produced, e.g. via D^* decays, can be detected in a generic LC detector without dedicated detectors in the rapidity range of $|y| < 1.5-2$. The charm detection efficiency, including fragmentation fraction and branching ratios, is typically around a few times 10^{-3} [8]. Hence the number of detected events from charm with such high p_T will be approximately a few thousand for the LC and several ten thousands for the PC. The latter will clearly allow for precision measurements of charm production and the gluon distribution in the photon. Some of the advantage of the PC over the LC is lost however due to the charm production at large y in case of the PC (see Fig. 4), which will go undetected with the presently planned detectors. The statistical precision of the measurements of $\frac{d^2\sigma}{dp_T^2 dy}$ will be approximately 5-10% at the LC and a few % at the PC.

In conclusion, the calculated cross-sections for heavy quarks (c and b) production in two photon collisions show a much higher sensitivity to the parton distribution parametrization of the structure of the photon in case of a Photon Collider compared to a e^+e^- Linear Collider. This does not depend on the particular scheme used to calculate the heavy quark cross-sections. Since the resolved photon contribution is to a large extend dominated by gluon induced processes, especially for a high energy PC, we conclude that heavy quark production provides indeed a sensitive probe of the gluon content of the photon. Combining the above features with the much larger cross-sections achieved at energies of the e^+e^- collisions at a PC favours this option for future photon structure research. A high luminosity e^+e^- collider which drives the PC collider will however be essential.

Appendix

The simplest Weizsäcker-Williams formula of the Equivalent Photon Approximation is used:

$$f_\gamma(x) = \frac{\alpha}{2\pi}(\frac{2}{x} - 2 + x)\log(\frac{\mu^2}{4m_e^2}) \tag{2}$$

where $x = \frac{E_\gamma}{E_e}$, m_e is the mass of the electron and μ is the energy scale of the process.

In case of the Compton (LASER) mode we use the original energy spectrum of unpolarized photons [1]:

$$\begin{aligned} f_\gamma(x) &= \frac{1}{\sigma_c^{np}}[\frac{1}{1-x} + 1 - x - 4r(1-r)], \\ \sigma_c^{np} &= (1 - \frac{4}{\kappa} - \frac{8}{\kappa^2})\ln(\kappa+1) + \frac{1}{2} + \frac{8}{\kappa} - \frac{1}{2(\kappa+1)^2}, \\ r &= \frac{x}{\kappa(1-x)}, \end{aligned} \tag{3}$$

where κ is a parameter giving the restriction of x value: $x < \frac{\kappa}{1+\kappa}$. It is argued [2] that the optimal value of κ is 4.83, which gives a cut of x, $x_{max} = 0.83$. We have chosen these values for this analysis. Note that the part of the spectrum with $x < 0.6$ is very sensitive to the technical parameters of the PC such as the size of the beam.

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	DD	DR	RR
FFNS	$\gamma + \gamma \to Q + \bar{Q}$	$g + \gamma \to Q + \bar{Q}$	$g + g \to Q + \bar{Q}$ $q + \bar{q} \to Q + \bar{Q}$
VFNS	$\gamma + \gamma \to Q + \bar{Q}$	$g + \gamma \to Q + \bar{Q}$ $Q(\bar{Q}) + \gamma \to Q(\bar{Q}) + g$	$g + g \to Q + \bar{Q}$ $q + \bar{q} \to Q + \bar{Q}$ $Q + \bar{Q} \to Q + \bar{Q}$ $Q + Q(\bar{Q} + \bar{Q}) \to Q + Q(\bar{Q} + \bar{Q})$ $Q(\bar{Q}) + q(\bar{q}) \to Q(\bar{Q}) + q(\bar{q})$ $Q(\bar{Q}) + g \to Q(\bar{Q}) + g$

Table 1: Parton reactions contributing to the process of heavy quark production in the massive (FFNS) and massless (VFNS) schemes.

	$c/\bar{c}$ at LC $\times 10^{-3}$	$b/\bar{b}$ at LC $\times 10^{-3}$	$c/\bar{c}$ at PC $\times 10^{-6}$	$b/\bar{b}$ at PC $\times 10^{-6}$
$\sqrt{s} = 300\, GeV$	565	45	37	6
$\sqrt{s} = 500\, GeV$	900	86	59	11
$\sqrt{s} = 800\, GeV$	1355	156	91	20

Table 2: Numbers of heavy quarks with $p_T > 10$ GeV produced at a LC and a PC for an integrated e^+e^- luminosity of 100 fb^{-1}, calculated in the FFNS scheme with the GRV parton parametrization.

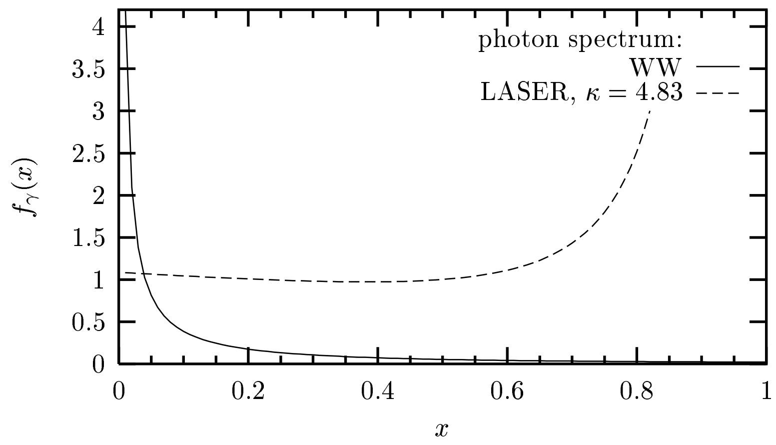

Figure 1: Comparison of the photon spectrum f_γ calculated with the Weizsäcker-Williams (WW) approximation, for $\mu = 10$ GeV, with the one calculated with the unpolarized laser photon spectrum (LASER), for $\kappa = 4.83$.

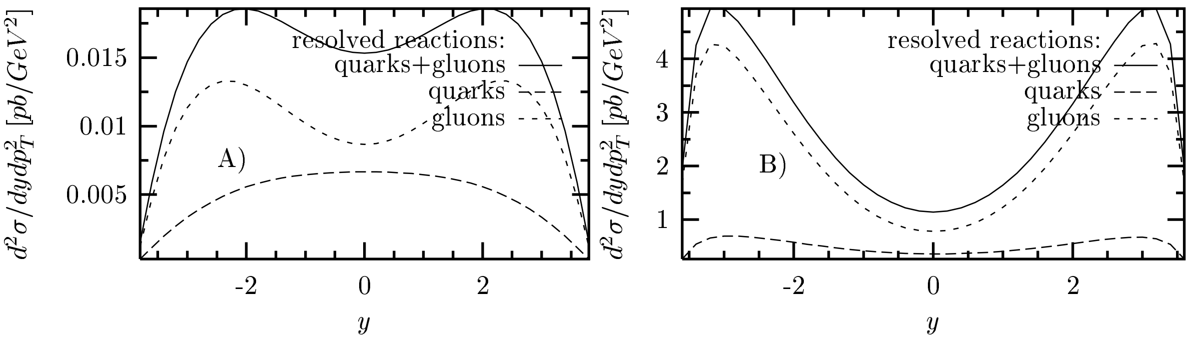

Figure 2: Comparison of parton reaction contributions which involve gluons with other parton reaction contributions to the resolved (DR+RR) part of the cross-section $\dfrac{d^2\sigma}{dp_T^2 dy}$ $(e^+e^- \to e^+e^- c/\bar{c}X)$ calculated in the VFNS scheme with GRV parton parametrization at $\sqrt{s} = 500$ GeV, $p_T = 10$ GeV: A) the WW photon spectrum, B) the LASER photon spectrum.

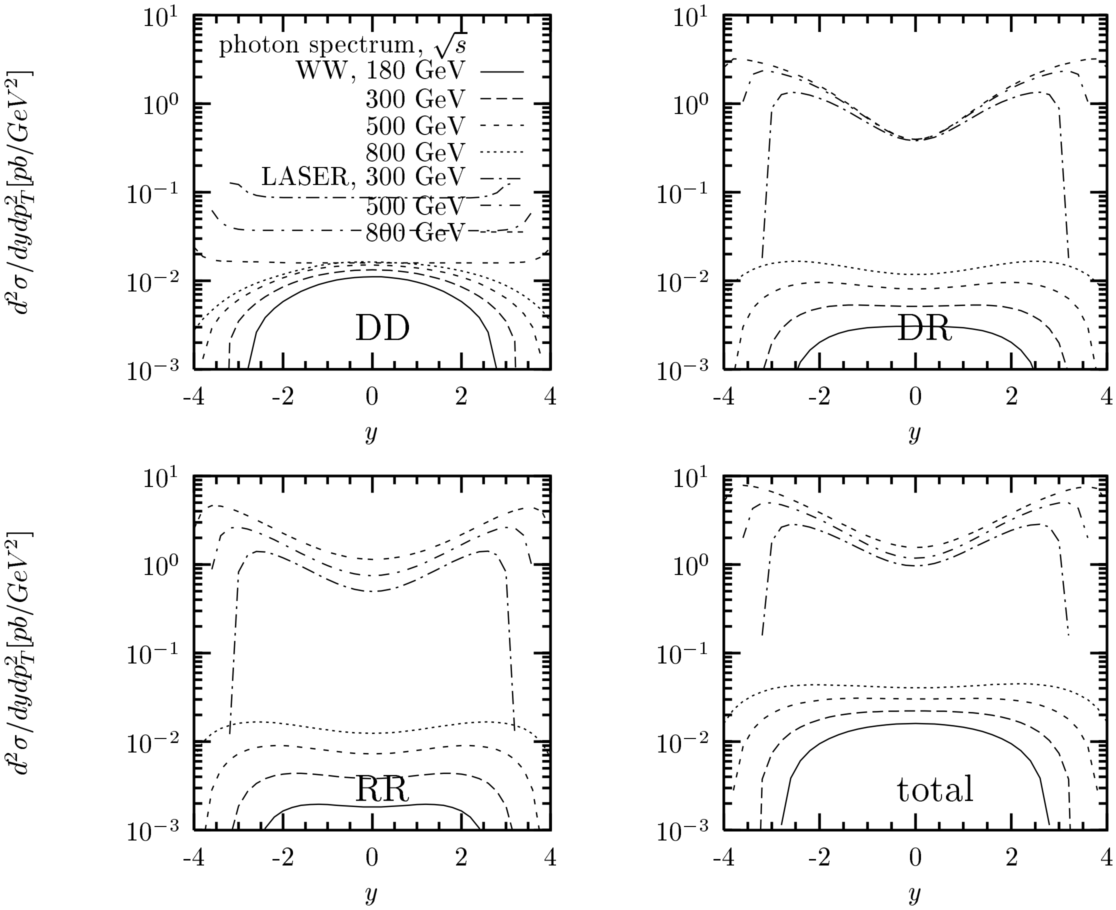

Figure 3: The cross-section $\dfrac{d^2\sigma}{dp_T^2 dy}$ $(e^+e^- \to e^+e^- c/\bar{c}X)$ at $p_T = 10$ GeV obtained with the GRV parton distribution parametrization in the VFNS scheme.

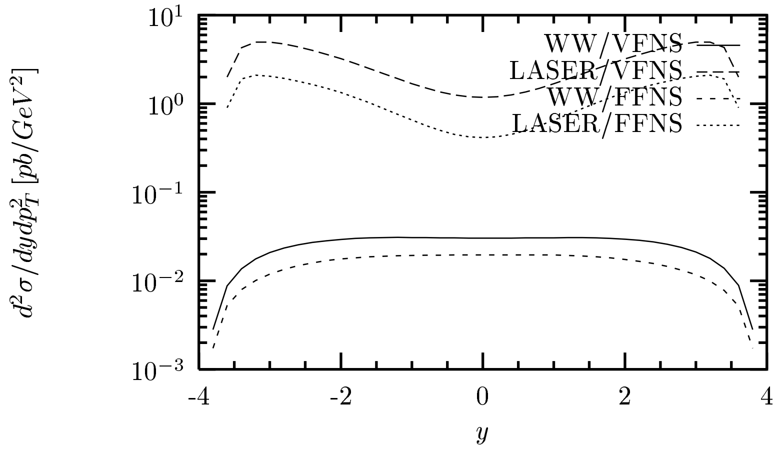

Figure 4: The total cross-section $\dfrac{d^2\sigma}{dp_T^2 dy}$ $(e^+e^- \to e^+e^- c/\bar{c}X)$ with $p_T = 10$ GeV and $\sqrt{s} = 500$ GeV calculated with the GRV parton distribution parametrization. Comparison between VFNS and FFNS schemes, and between the LASER and WW photon spectra.

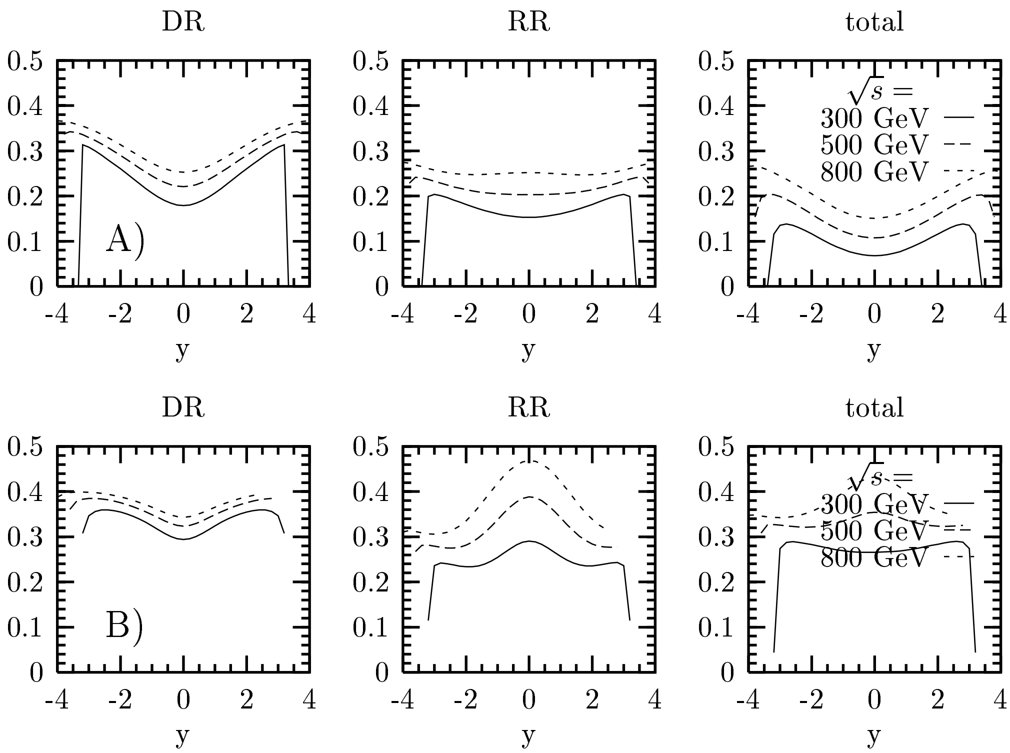

Figure 5: The ratio $\frac{GRV-SAS1d}{GRV}$ of the cross-section $\frac{d^2\sigma}{dp_T^2 dy}$ $(e^+e^- \to e^+e^- c/\bar{c}X)$ for $p_T = 10$ GeV, in VFNS scheme, for two photon spectra: A) WW, B) LASER

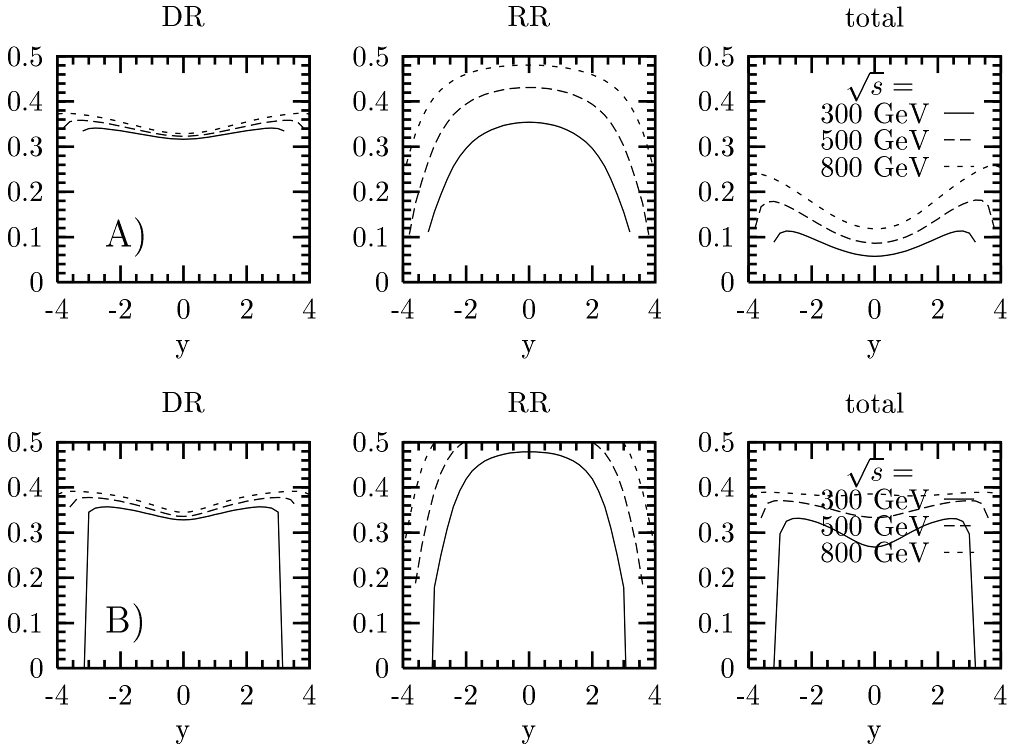

Figure 6: The ratio $\frac{GRV-SAS1d}{GRV}$ of the cross-section $\frac{d^2\sigma}{dp_T^2 dy}(e^+e^- \to e^+e^- c/\bar{c}X)$ for $p_T = 10$ GeV, in FFNS scheme, for two photon spectra: A) WW, B) LASER